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WEAR OF HOMOGENEOUS AND COMPOSITE MATERIALS UNDER CONDITIONS OF--ETC(U)
1977   S L RICE, R SOLECKI   AF-AFOSR-3087-76

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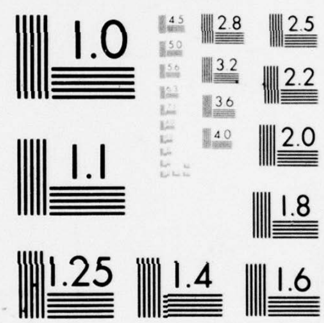

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THE UNIVERSITY OF CONNECTICUT
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[redacted] Scientific Report

to

United States Air Force

Air Force Office of Scientific Research

Wear of Homogeneous and Composite Materials Under

Conditions of Repeated Normal and Sliding Impact

(See 1473)

This report documents research conducted under AFOSR Grant 76-3087 during the period June 30, 1976 through July 7, 1977.

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Principal Investigator

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Abstract

This report describes experimental and analytical investigations in the area of wear of materials due to repeated impact loading. A reciprocating impact wear test apparatus is utilized to provide controlled, repetitive impacts between a material specimen and a counterface. The impulsive loading may be purely normal or a condition of relative sliding may be introduced during the impact event. A wide variety of materials have been investigated in both normal and sliding impact modes. These include two polymers, a composite, and several metals. The wear behavior of these materials is investigated as a function of peak impulsive load, relative sliding velocity, and number of impact load cycles. Weight loss and/or surface profile data are obtained as a function of these parameters. Scanning electron microscope studies of the wear surface and of sub-surface sections suggest that delamination is the operative mechanism for some materials but not for others.

Analytical investigations are directed toward determination of the states of stress in material specimens undergoing controlled, repetitive impact. Results are derived from the theory of elasticity by application of the Laplace transformation combined with the triple, finite Fourier transformation. Correlations between sub-surface stress levels and wear debris formation are sought.

Experimental

Impact wear testing has been accomplished by means of a novel apparatus described earlier (1). This device is designed to:

1) provide synchronized repetitive normal or sliding impact;
2) provide continuous, uniform relative sliding between impacting materials in the sliding wear mode of operation;
3) provide for the measurement of variables critical to the study of the process of impact wear;
4) provide wide variability and control of experimental parameters.

Testing has been conducted on the following materials:

1) Titanium alloy: Ti-5Al-5Sn-2Zr-2Mo-0.25Si (RMI-5522S)
2) Titanium alloy: Ti-6Al-5Zr-0.5Mo-0.25Si (IMI-685)
3) Aluminum alloy: Al-5.5Cu-0.4Bi-0.4Pb (2011-T3)
4) Aluminum alloy: Al-4.4Cu-0.6Mn-1.5Mg (2124)
5) High Strength Steel: 14Co-10Ni-2Cr-1Mo-0.16C (AF-1410)
6) Graphite Epoxy Composite: SP-288T300 (3M)
7) Polytetrafluoroethylene: Extruded PTFE (Teflon)
8) Polyoxymethylene: Extruded Acetal Resin (Delrin).

The testing and data acquisition procedures consist of the following steps. First, materials are machined to a stepped-shaft configuration. The major diameter of this stepped-shaft fits into the specimen holder on the impact wear testing machine, while the minor diameter end constitutes the specimen striking surface. By selecting specimen impact diameters, variations in stress levels are easily obtained. Second, specimens are subjected to an initial "running-in" period on the machine. This procedure guarantees full surface impacts and a uniform starting condition for all specimens. A reference specimen which is not subjected to the run-in procedure is retained for comparison purposes in sub-surface microscopy examination. Third, initial surface profile and/or weight data are obtained. Fourth, a series of specimens is run in the impact wear testing machine. For each data set, a peak impact load is specified as is the relative sliding velocity. For the case of pure normal impact, the relative sliding velocity is zero. Specimens are run under the above specified conditions for varying numbers of impact cycles. Typically, different specimens are run at 1,000; 50,000; 100,000; 150,000 and 250,000 cycles for a given peak impact load and relative sliding speed. Fifth, final surface profile and/or weight loss data are obtained. In the case of weight loss measurements, these data are plotted as a function of number of cycles of impact. Comparisons are drawn for a given material as a function of peak impact load and/or relative sliding velocity. Similarly, comparisons are drawn between different materials for specimens subjected to identical peak impact loads, relative sliding velocities and numbers of impact cycles. Sixth, specimens are prepared for surface examination using scanning electron microscopy. The nature of the worn surface is evaluated, with particular attention directed to the formation of wear lamina. In some cases, the counterface (17-4 PH stainless steel) is likewise examined. Seventh, selected specimens are sectioned parallel to the wear track direction. These sectioned surfaces are then prepared for sub-surface SEM examination. This procedure includes mounting, vibromet or electrolytic polishing, etching as appropriate, light microscope examination, re-polishing and etching as required, vapor deposition, etc. Eighth, sub-surface SEM examination is conducted. In this procedure, particular attention is directed toward the formation of voids and cracks, and to the extent of sub-surface plastic deformation. Ninth, in some cases an additional sectioning is performed, perpendicular to the wear track direction. Additional sub-surface SEM examinations are then performed as indicated above.

Some of the results from the above testing program have been reported (1). In particular, the polymeric materials appear to wear by a process of delamination. Wear increases with increased relative sliding velocity, as does the process of surface and sub-surface crack initiation. Increasing numbers of impact cycles tend to refine microcrack patterns. The impact wear rate for teflon far exceeds that for delrin.

Results from studies of the metallic and composite materials are to be published (2). In general, wear rates are higher at lower relative sliding velocities, and wear rates in purely normal impact are negligible compared to those in compound impact. For the two titanium alloys tested, peak impulsive loads of 334 Newtons were applied to flat ended specimens of diameter 0.64 cm. Relative sliding speeds of 3.19 and 5.32 m/sec were employed in separate series of tests. The IMI 685 alloy shows only a minor sliding velocity dependence, while the RMI 5522S shows significantly less wear at the higher velocity than at the lower. It should be noted that microstructural variables may play a part in the overall impact wear resistance of RMI 5522S. For the tests reported here, the alloy microstructure consisted of roughly 90% primary alpha and 10% transformed beta, giving high strength and good ductility (3). Other microstructures may yield improved wear resistance. The IMI 685, on the other hand, was tested in its unique recommended microstructural condition, consisting of 100% transformed beta (3). Surface SEM examination indicates that some delamination is occurring for both titanium alloys. Significant transfer films, however, suggest that adhesive processes are likewise important.

For the two aluminum alloys tested, peak impulsive loads of 133 Newtons were applied to flat ended specimens of diameters ranging from 0.32 to 0.64 cm. Relative sliding speeds varying from 2.66 to 5.85 m/sec were employed in separate test series. It was found, in similar tests, that large diameter specimens exhibited a greater weight loss than smaller diameter specimens. This is attributed simply to the difference in effective contact area during impact. Further, in a special series of tests designed to explore reproducibility of data and velocity-dependence, the phenomenon of higher wear rates at lower relative sliding velocities was confirmed.

The 2124 alloy is considerably more impact wear resistant than is the 2011-T3. Not only are wear rates less, the mechanism of debris formation appears to be different. Both surface and sub-surface SEM examination reveals signs of delamination in the 2011-T3, but not in the 2124. Surface microscopy shows wear lamina, and sub-surface microscopy shows significant void and crack formation in the 2011-T3. These features are absent in the 2124, despite considerable sub-surface plastic deformation. The reason for the difference is thought to be due to the lead and bismuth constituents in the 2011-T3. These elements are present to make this alloy "free machining"; hence, they effectively serve as crack nucleation sites, allowing the delamination mechanism to occur. In contrast, the 2124 wears by adhesive and plowing mechanisms.

The graphite epoxy composite material was machined with the graphite fibers oriented longitudinally in the stepped-shaft specimen configuration. These specimens were tested at a peak impulsive load of 160 Newtons; spherical ended specimen diameters were 0.64 cm; relative sliding velocities were 0.0, 2.66 and 4.79 m/sec. Weight loss data were two orders of magnitude less than those obtained for other materials tested at comparable numbers of impact cycles. Accordingly, with fiber orientation as indicated, this composite material appears to possess good impact wear resistance.

The AF-1410 steel was tested in two conditions: "tough" and "strong". In both cases, the material was double austenitized, quenched at each interim, and aged. Different aging temperatures were used to obtain the maximum toughness ("tough") and maximum strength ("strong") conditions. The material was subjected to peak impulsive loads of 334 Newtons; flat ended specimen diameters were 0.32 cm; relative sliding velocity was 3.72 m/sec. These parameters were used for both the "tough" and "strong" material conditions. The material in the maximum strength condition was found to wear at a slightly greater rate than that in the maximum toughness condition. Further, with this material, the first case of significant "two body" wear was observed. With all other materials tested to date, the 17-4 PH stainless steel counterface was essentially unworn. Indeed, in many cases with other materials, a transfer film was deposited on this counterface, giving rise to a weight gain. However, with the AF-1410 steel, the stainless impact cap did experience significant weight loss, many times greater than that experienced by the striking 1410 material. The "strong" condition produces slightly more wear on the stainless impact cap than does the "tough".

Analytical

In order to effectively model material wear rates under impact loading, one must first develop analytical models which allow the prediction of time varying stress levels resulting from such loading. This class of problems is one of the most challenging in solid mechanics.

However, when sub-surface stress distributions are obtained, correlations with experimentally observed wear phenomena are expected. Such correlations should lead to predictive models for the wear of materials under impact loading conditions.

Our problem has a "built-in" difficulty: we are dealing with a "controlled" impact as contrasted with various forms of "free" impact considered by others. In addition, the motion of the far end of the striking specimen is not known exactly, due to the dynamic response characteristics of the overall system and the existence of tolerances between moving components. Hence, the unknown motion of the far end of the specimen must be determined. The problem tackled first consisted of the analysis of a one dimensional finite elastic rod striking normally and without friction the surface of an elastic half-space. The motion of the far end was assumed to be controlled by an unknown function of time $f(t)$ (4). On the other hand, the reaction $R(t)$ of the half-space is known, as it is the transducer output. This gives an additional condition for determining $f(t)$.

This relatively simple model hardly resembles the actual physical phenomenon: the specimen is not a one dimensional rod; the counterface (modeled by the half-space) moves; and friction is present at the interface of the two solids due to relative sliding during compound impact. Nonetheless, the solution of this problem provided insight and valuable information concerning the viability and practicality of analytical methods subsequently applied for the study of other, more realistically formulated problems.

The simplicity of the above physical model, however, does not necessarily imply the simplicity of the resulting analytical description:

the procedure adopted in (4) is quite complicated indeed. First, the finite Fourier transformation is applied to eliminate the space variable from the equation of the motion of the rod. The solution of the resulting ordinary differential equation depends on the unknown "controlling" function f(t), and on the unknown, time-dependent displacement of the impacting end. This last quantity can be eliminated by requiring the continuity of the displacements at the interface between the rod and the impacted half-space. Since the concentrated force theoretically produces an infinite displacement at the point of application, it was necessary to approximate this force by an uniform, time-dependent load impacting over a disc-shaped area enclosing the impact "point". Comparison of the interface displacements and stresses of the two solids (the problem of sudden application of a uniform load at the disc-shaped part of the surface of an infinite elastic half-space was solved previously by Eason (5)) lead to the Volterra integro-differential equation for the unknown vertical interface displacement. This equation was solved formally by applying Laplace transformation. The inversion of the Laplace transform of the unknown function presented considerable difficulty. However, utilization of continued fractions (6) proved to be helpful in the final solution.

A similar procedure is applied to the somewhat more complicated problem of the controlled, normal, frictionless impact of an elastic cylinder on a rigid half-space (7). The less realistic interface condition is offset by the benefit of discriminating between stresses at various points of any given cross-section of the specimen.

Since it was interesting to evaluate - even very imperfectly - the influence of friction (due to relative sliding) on the stress level, a certain static problem was solved with the expectation that the resulting stresses should give a rough verification of the much more involved solution of the dynamical problem.

To this end it was assumed that an elastic parallelepiped rests on a rigid half-space which reacts not only by means of normal stress but also through tangential stresses proportional to the normal stresses, thus modeling friction due to relative sliding. The far end of the parallelepiped was subject to uniform vertical displacement (representing the static counterpart of the controlling function f(t)). It was also assumed that the vertical faces of the elastic solid were not allowed displacement in the normal direction. Even though such constraints are not present in the real specimen whose vertical surface is stress-free, it is expected that the deviation in the stress level is acceptable as long as the stresses are not calculated in the vicinity of the vertical boundaries. On the other hand, this assumption results in considerable simplification of the algebra.

Application of the triple, finite mixed Fourier transformation and utilization of the available boundary conditions (including the condition that the reaction at the interface is known and equals R = max R(t)) lead to the following infinite system of algebraic equations with respect to the Fourier coefficients A_m of the interfacial shear stresses:

$$\sum_{m=1,3}^{\infty} \frac{A_m}{m} = \frac{\pi k R}{4\mu a} \tag{1}$$

$$\left[\frac{kA_i}{(\lambda+2\mu)\sinh^2\left(\frac{i\pi b}{a}\right)}\right] \cdot \left[\mu \sinh\left(\frac{2i\pi b}{a}\right) - 2\pi i \frac{b}{a}(\lambda+\mu)\right] - \frac{8}{\pi} \sum_{m=1,3}^{\infty} \frac{mA_m}{m^2-i^2} = 0 \quad i = 1,2,\ldots \tag{2}$$

where k is the coefficient of friction, λ and μ are Lamé constants, and b and a represent the height and the length of the side of the cross-section. Once A_m are found by approximate solution of this system, the stresses can be found relatively simply. For instance, the following expressions were derived for the interfacial normal and tangential stresses:

$$\sigma_{yy} = \frac{R}{a^2} + \mu_m \sum_{=1}^{\infty} \left[\frac{A_m}{\sinh^2(\frac{m\pi b}{a})}\right]\left\{- \frac{1}{1-\nu}\, m\pi\frac{b}{a} + \frac{(1-2\nu)\sinh(\frac{2m\pi b}{a})}{(1-\nu)}\right\} \cos(\frac{m\pi x}{a}) \quad (3)$$

$$\sigma_{xy} = 2\mu \sum_{m=1}^{\infty} A_m \sin(\frac{m\pi x}{a}) \quad (4)$$

Some numerical results for interfacial and sub-surface values of various stresses are given in the table below for the case a=b.

	interfacial					sub-surface (relative distance from the interface = 0.05)				
Relative distance from the vertical face: x/a =	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7
$a^2\sigma_{yy}/R$	1.031	1.012	0.996	0.980	0.962	1.019	1.008	0.999	0.990	0.980
$a^2\sigma_{xy}/R$	0.309	0.304	0.299	0.294	0.289	0.243	0.249	0.249	0.244	0.232

When the above problem is coupled with the procedure adopted in (4), one can go one step further and attempt to solve the following impact problem with friction (8): controlled impact of the parallelepiped described before. This is done in the following way: triple Fourier transformation is used again in conjunction with Laplace transformation. This leads to the derivation of a similar infinite system of algebraic equations as shown above. This time, however, the A_m are functions of the Laplace parameter s and so are the functions appearing therein (including R). In addition, the unknown function f(t) is defined as the solution of an integro-differential equation. The inversion of the Laplace transformation becomes extremely complicated in this case: The problem is attacked by representing all terms as power series in 1/s. In particular: $A_m = g_{m1}/s + g_{m2}/s^2 + \ldots$ This expansion represents considerable algebraic difficulty. Once this is performed, however, it then seems tempting to invert term by term the approximate values of g_{m1}, g_{m2}, etc. obtained by solving a doubly infinite system of algebraic equations. This procedure, however, is known to lead to a solution converging only for small values of time. Such a solution is of limited interest to us because the stress wave is reflected several times from the far end before the transducer output R(t) reaches its peak. Therefore, this series in 1/s is replaced by continuous fractions in the way described by Akin and Counts in (9). Then the so-called "convergents" are inverted in a usual way giving results free from the above limitation. The resulting stress distributions are expected to correlate with experimental observations of sub-surface plastic deformation and void and crack formation. For at least some materials, these phenomena are thought to be intimately related to the formation of wear debris.

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER 19 AFOSR TR-77-0857 18	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 WEAR OF HOMOGENEOUS AND COMPOSITE MATERIALS UNDER CONDITIONS OF REPEATED NORMAL AND SLIDING IMPACT.		5. TYPE OF REPORT & PERIOD COVERED 9 ~~INTERIM~~ Rept. for 30 Jun 1976-7 Jul 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 STEPHEN L. RICE ROMAN SOLECKI		8. CONTRACT OR GRANT NUMBER(s) 15 AF-AFOSR 76-3087-76
9. PERFORMING ORGANIZATION NAME AND ADDRESS THE UNIVERSITY OF CONNECTICUT ~~SCHOOL OF ENGINEERING~~ STORRS, CONNECTICUT 06268 Inst of Materials Science		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 2307B2 17 B2 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BLDG 410 BOLLING AIR FORCE BASE, D C 20332		12. REPORT DATE 11 1977
		13. NUMBER OF PAGES 14 12 18p.
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

WEAR
TRIBOLOGY
FRICTION
IMPACT
SLIDING CONTACT FATIGUE
MECHANICS
STRUCTURAL MATERIALS
COMPOSITE MATERIALS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes experimental and analytical investigations in the area of wear of materials due to repeated impact loading. A reciprocating impact wear test apparatus is utilized to provide controlled, repetitive impacts between a material specimen and a counterface. The impulsive loading may be purely normal or a condition of relative sliding may be introduced during the impact event. A wide variety of materials have been investigated in both normal and sliding impact modes. These include two polymers, a composite, and several metals. The wear behavior of these materials is investigated as a function of peak impulsive

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INSTITUTE OF MATERIALS SCIENCE

The Institute of Materials Science was established at The University of Connecticut in 1966 in order to promote the various fields of materials science. To this end, the State of Connecticut appropriated $5,000,000 to set up new laboratory facilities, including approximately $2,150,000 for scientific equipment. In addition, an annual budget of several hundred thousand dollars is provided by the State Legislature to support faculty and graduate student salaries, supplies and commodities, and supporting facilities such as various shops, technicians, secretaries, etc.

IMS fosters interdisciplinary graduate programs on the Storrs campus and at present is supporting five such programs in Alloy Physics, Biomaterials, Crystal Science, Metallurgy, and Polymer Science. These programs are directed toward training graduate students while advancing the frontiers of our knowledge in technically important areas.